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Numerical Unsaturated Flow Model of Railway Drainage Systems

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Abstract: Substandard drainage assets are considered to be a major cause of flooding, earthwork failures, and deficient track geometry**.** Considering the deterioration of track materials due to cyclic loads and tamping forces, the impact of more frequent extreme rainfall events is likely to lead towards higher rates of hydraulic overloads in the drainage system, earthwork failures, and service disruptions. Therefore, the development of a numerical model could be able to describe the ageing track bed materials and provide an alternative tool for the simulation of the flow through the porous media used in the construction of railway tracks. In this paper the model HYDRUS is tested to simulate the drainage of trackbed materials under laboratory controlled conditions prior its application on actual railway drainage case studies.

Keywords: railway drainage systems; unsaturated flow; railway flooding

1. INTRODUCTION

Ballast and subballast track layers must be able to transmit the loads to the subgrade as much as allowing the efficient drainage of water entering in to the tracks. The efficient infiltration of water through the trackbed layers is essential for the delivery of an appropriate transportation service. Substandard drainage assets are a major cause of flooding, earthwork failures, and deficient track geometry.

The currently available railway drainage guidelines in the UK - based on agricultural methods– are not able to describe the flow processes in these porous media or neither address the changes in its hydraulic properties over time (Network Rail, 2010). Other approaches have been based on the application of the Dupuit-Forchheimer assumptions (Youngs and Rushton, 2009; Rushton and Ghataora, 2009). However, this theory may not be applicable in all the railway drainage typologies or describe transient flow (Kong et al., 2016).

In order to avoid inaccuracies on the groundwater table level (Kong et al., 2016), applying a physically based variably saturated-unsaturated flow model could appeal describe fouled ballast (Cui, 2016), and the subsurface flow mechanisms involved. This paper presents preliminary results of the simulation of railway drainage system materials under laboratory conditions using a physically based variable saturated flow model.

2. MATERIALS AND METHODS

The model used in this study is HYDRUS 2D/3D version 2.05. Due to the lack of data of the hydraulic properties of the track materials at the stations, a preliminary calibration and validation of the model was performed using the results and layers characteristics of a flume test under steady state conditions (Heyns, 2000) These soil parameters will be used for future simulations of the drainage outfall at Garforth and Newbury Park (UK).

2.1 Governing equations

HYDRUS solves the modified form of the Richards' equation for variable saturated flow conditions:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{ij}^{A}\right)\right] - S \quad (1)$$

Where θ is the volumetric water content [L^3L^{-3}], h is the pressure head [L], S is a sink term [T^{-1}], x_i (i=1,2) are the spatial coordinates [L], t is time [T], K_{ij}^A are components of a dimensionless anisotropy tensor K^A. K is the unsaturated hydraulic conductivity function [LT^{-1}], and it is given by:

$$K(h,x,y,z) = K_s(x,y,z)K_r(h,x,y,z) \quad (2)$$

Where K_r is the relative hydraulic conductivity and K_s the saturated hydraulic conductivity [LT^{-1}].

Van Genuchten –Mualem model was used to define the soil hydraulic functions, given by the following expressions:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} \text{ for h < 0} \quad (3)$$

$$\theta(h) = \theta_s \text{ for h} \geq 0 \quad (4)$$

$$K(h) = K_s S_e^l\left(1-\left(1-S_e^{1/m}\right)^m\right)^2 \quad (5)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (6)$$

$$m = 1 - \frac{1}{n}\,;\,\mathrm{n} > 1 \quad (7)$$

Where θ_r and θ_s denote residual and saturated volumetric water contents [L^3L^{-3}], respectively; S_e is the effective saturation [−], α [L^{-1}], and n [−] are retention curve shape factors, and l is a pore connectivity parameter [−].

2.2 Flume test description

During the flume tests performed by Heyns (2000) the flow processes of a rail track formed by a ballast layer and a subballast layer of 127 and 152.4 cm, respectively, were observed. Six piezometers at the bottom of the flume (Figure 1) recorded the water table level under a different rainfall conditions (13 to 75 mm/h). Different slopes between the ballast and the subballast were also tested (0, 1, 3, and 5%). The draining characteristics of several subballast material were evaluated adding fines (Table 1)

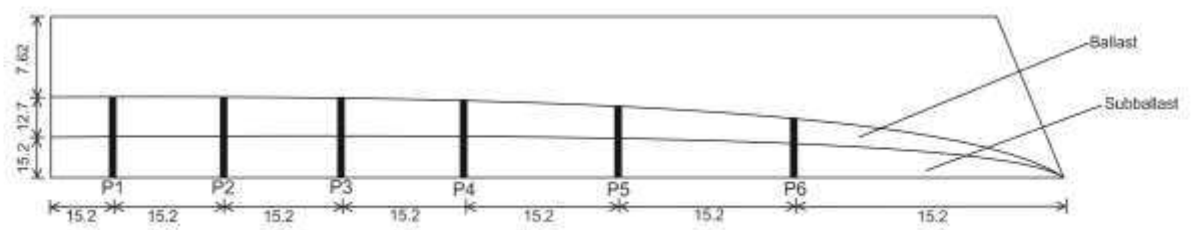

Figure 1. Description of Heyn's experiments with dimensions in cm. Position of the piezometers is indicated in bold as well as the approximate position of ballast and subballast layers. The flume was 35.4 cm wide. Rainfall was simulated over 188 cm at the top of the flume.

Table 1. Information provided about the materials used during Heyns' tests (Heyns, 2000).

Subballast Type	Description	Fine content (%)	K_s (m s^{-1})	Specific retention (%)	Dry Unit Weight (kg m^{-3})
Subballast 1	Gravel	0	5.8×10^{-4}	15.8	1938
Subballast 2	Gravelly sand	10	7.5×10^{-5}	15.9	1954
Subballast 3	Gravelly sand	18	6.6×10^{-6}	15.9	1986

2.3 Boundary conditions

A time-variable atmospheric boundary condition was applied to include the rainfall intensities; no flow boundary conditions were added at the sides of the flumes and are also considered at the limits of the drainage area. A seepage boundary condition was included at the flume outlet during the Heyn's experiments simulation.

2.4 Model calibration and validation

The initial Van-Genuchten parameters used in the calibration were based on data from the literature (Filipović et al., 2014; Thoma et al., 2014). The Heyns' experiments data were used to calibrate α and n over the cumulative outlet depths of events with 0.762 and 1.168 cm/h rainfall intensities. Ballast representation was assumed to be similar to subballast 1 due to the open structure of American ballast (Rushton and Ghataora, 2009). Nash-sutcliffe Efficiency coefficient (NSE) was determined to assess the accuracy on the prediction of cumulative outflow depths. The Relative Percentage Difference (RPD) was used to evaluate the difference between the simulated and the observed cumulative depth.

3. RESULTS AND DISCUSSION

The resulting parameters of the calibration are reported in Table 2. Comparison of preliminary HYDRUS results with the flume test yield similar cumulative outflow depths and provided confidence on the Van Genuchten parameters used. The NSE coefficients for the validation events with 0.635 cm/h and 0.559 cm/h rainfall intensity were 0.998 and 0.963, respectively (Figure 2). The RPD of the total cumulative depths showed a good prediction of the outfall values with ratios of 1.34% and 2.29%.

Table 2. Calibrated Van Genuchten parameters for ballast and subballast 1 media.

Track material	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm h^{-1})	l
Ballast	0.005	0.4	0.2	3	2088	0.5
Subballast 1	0.005	0.4	0.2	3	208.8	0.5

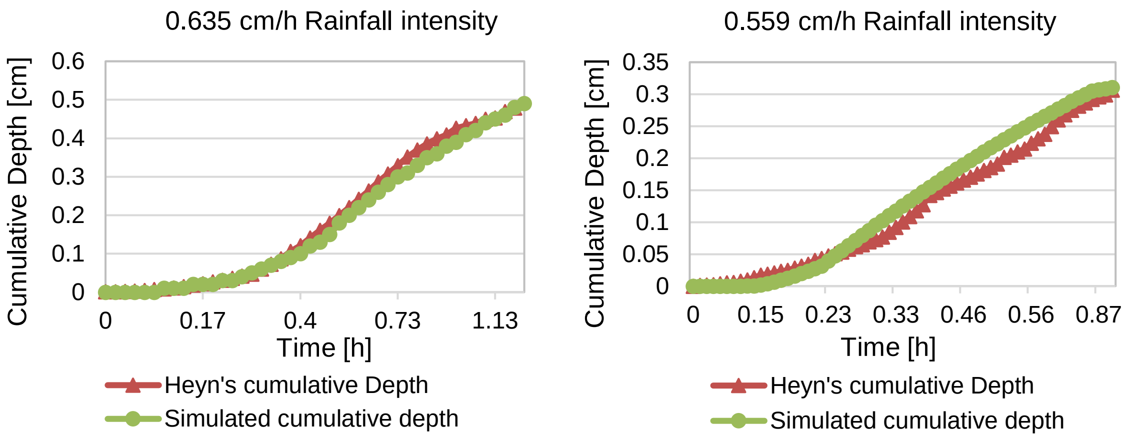

Figure 2. Comparison of cumulative outflow depth during Heyn's experiments and simulation results provided by HYDRUS.

CONCLUSIONS

The unsaturated flow model used in this study describes satisfactorily the steady state flow within the railway track media. The proposed soil hydraulic parameters provide confidence on the description of the hydraulic processes. Therefore, these will be used to apply the model to describe the drainage of Newbury Station in London and Garforth Station in Leeds (UK).

The use of a variably saturated-unsaturated model constitutes a novel approach for the simulation a railway drainage system, allowing to simulate the changes on ballast and subballast media over time. However, the limitations on studies available and the difficulties of the hydraulic characterisation of the track layers are the main challenge in the application of a physically based model.

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